Engineered Conversion and Stabilization Pathways for Biomass Carbon

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Estimated Global Potential of CDR in 2050

CDR Pathway	Gigatons of CO_2 per year
Afforestation and reforestation	0.5 – 3.6
BECCS	0.5 – 5.0
Biochar	0.5 – 2.0
Enhanced weathering	2.0 – 4.0
Direct air capture	0.5 – 5.0
Soil carbon sequestration	Up to 5.0

What about BiCRS?

Fuss et al. 2018

Biomass Carbon Removal and Storage (BiCRS)

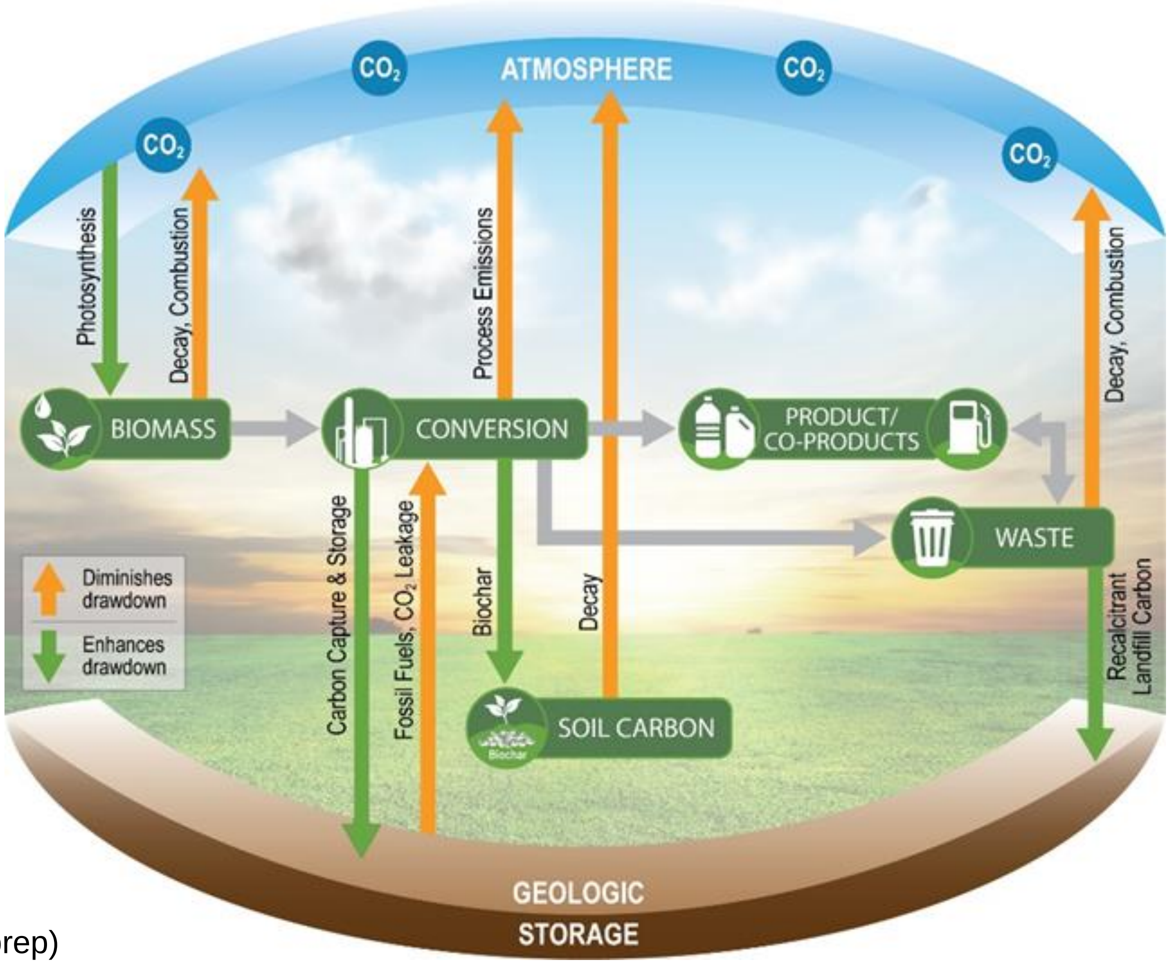
- Use biomass to remove CO_2 from the atmosphere
- Store that CO_2 underground or in long-lived products
- Do no damage to—and ideally promote—food security, rural livelihoods, biodiversity conservation and other important values

BECCS → BiCRS

Bioenergy → Biocarbon

Paradigm shift?

Aines et al. 2021



Dees et al. 2022 (in prep)

The Bioeconomy

The bioeconomy encompasses the production of renewable biological resources from the agricultural, forestry, and aquaculture sectors, and the conversion of these renewable resources and waste streams into value added products, such as food, feed, bioenergy, and **<u>other bio-based products</u>**

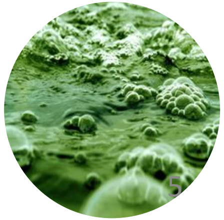








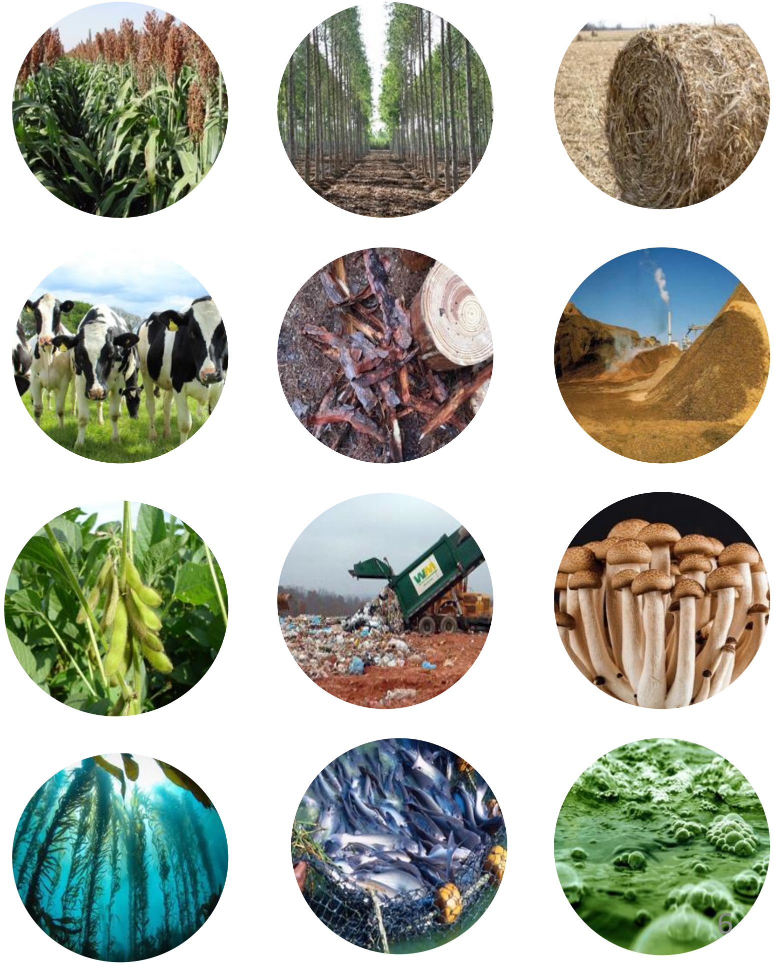




The Bioeconomy

In the US: more than 22% of total economic activity, valued at more than $1 trillion, and employs ~28% of the workforce

Approximately 30 – 50% of mass in food and agricultural systems is lost between biomass cultivation and end product sale



2016 BILLION-TON REPORT

Advancing Domestic Resources for a Thriving Bioeconomy

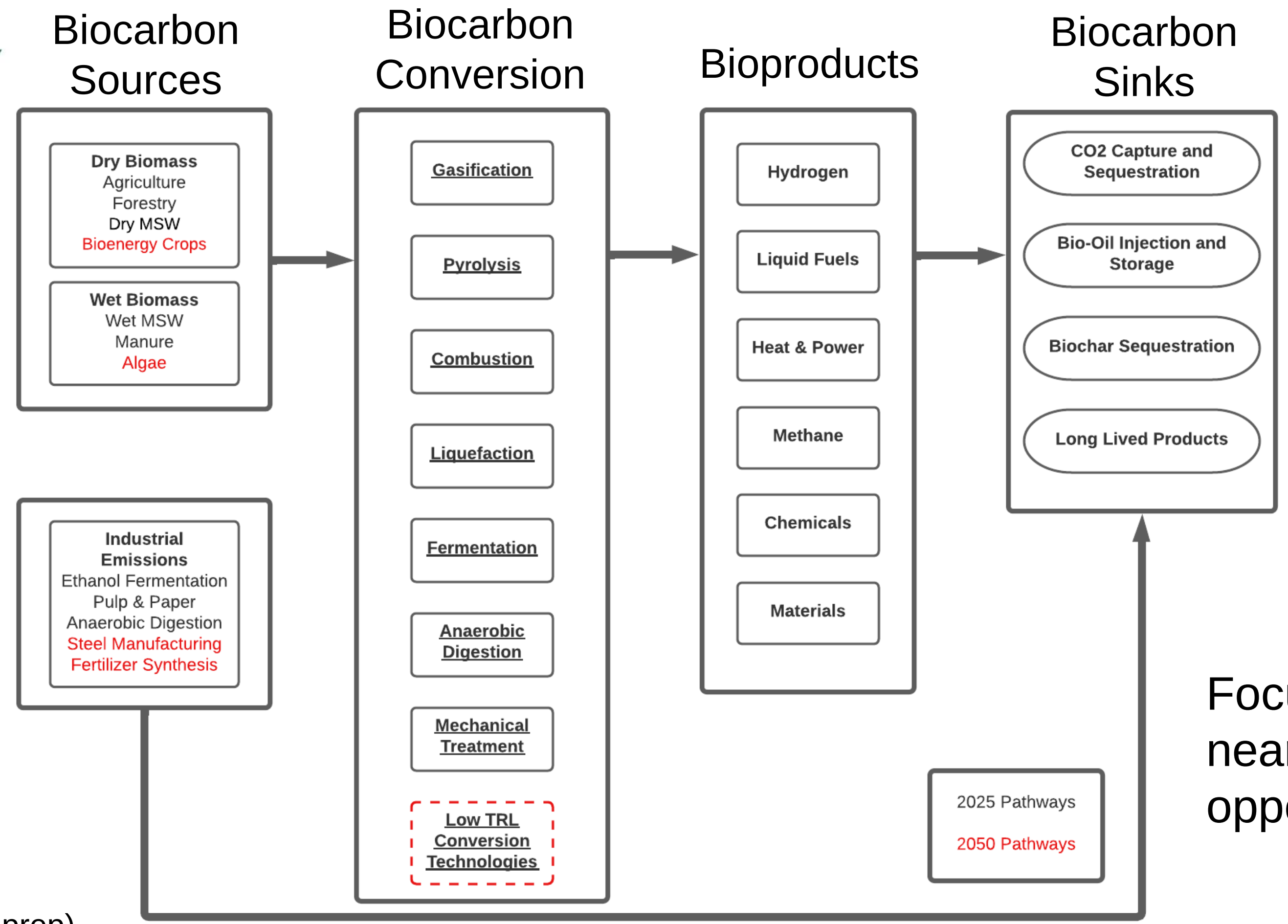
Volume I | July 2016

U.S. DEPARTMENT OF ENERGY

1 billion tons of biomass per year by 2040
Assume 50% carbon
500 million tons of carbon per year
1.85 billion tons of biogenic CO_2 fixation per year
Not including the carbon flows in the existing bioeconomy…

NC STATE UNIVERSITY

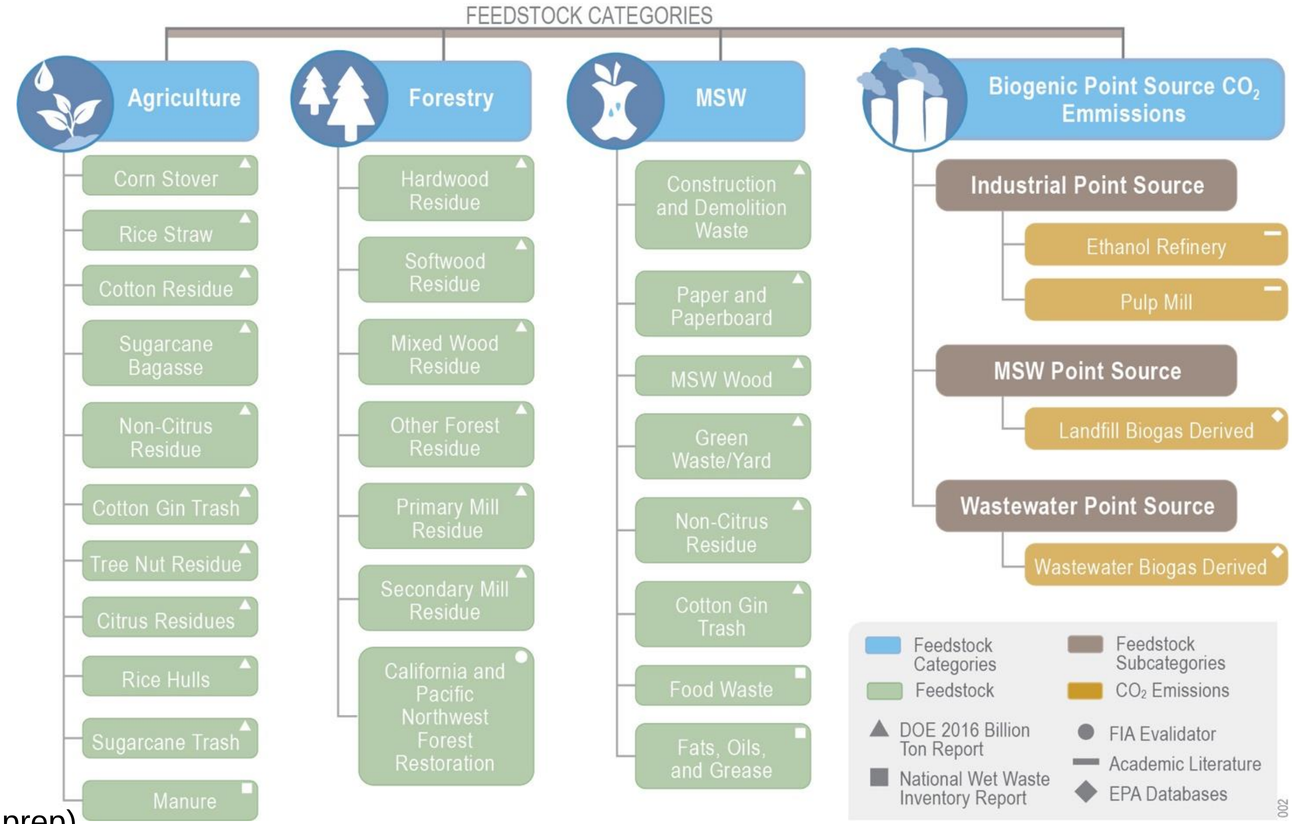
U.S. DEPARTMENT OF ENERGY



Focusing on near-term opportunities

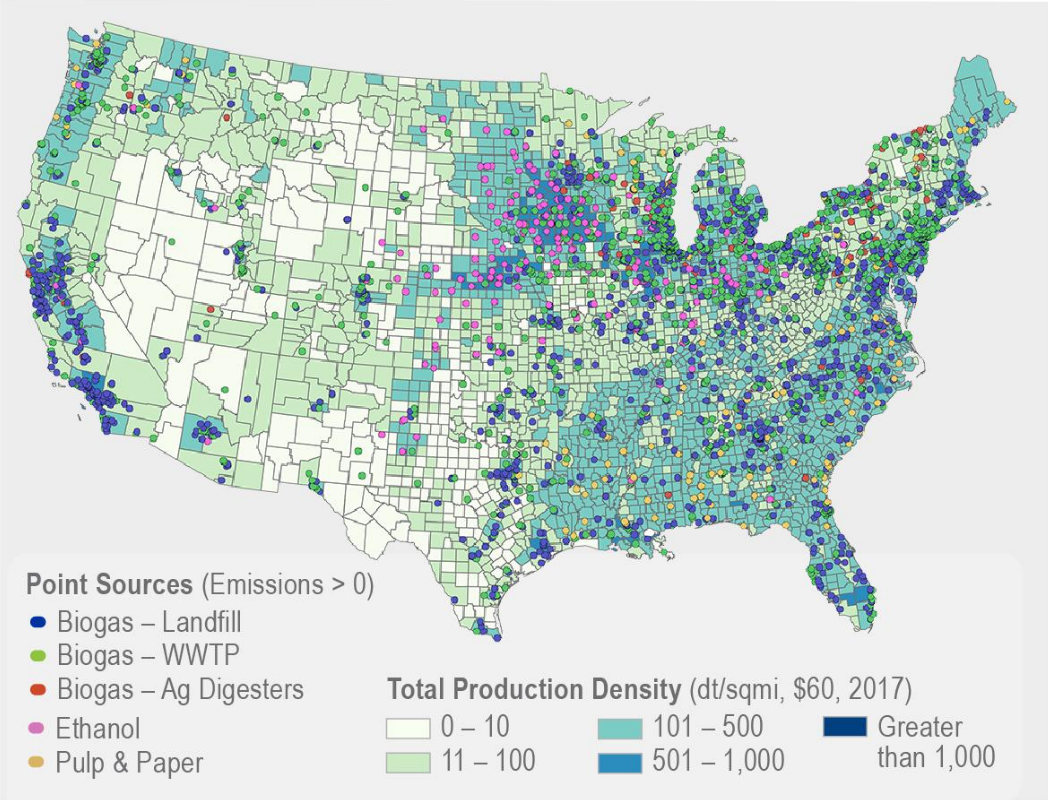
Aines et al. 2022 (in prep)

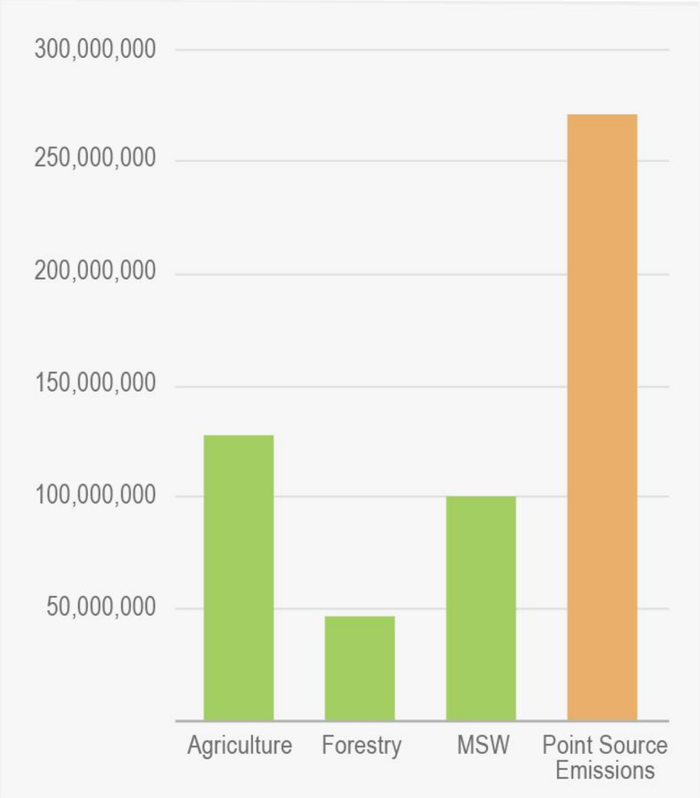
Biocarbon Sources



Aines et al. 2022 (in prep)

Biocarbon Sources





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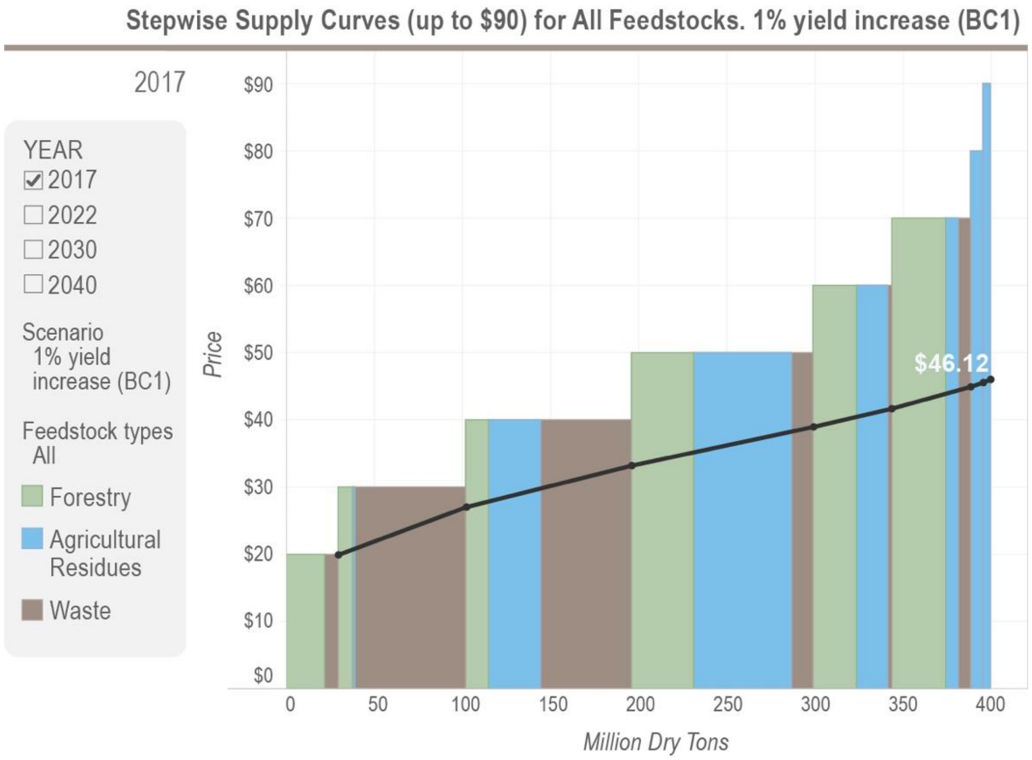
Biocarbon Sources



300 million tons of biomass waste per year @ < $50 per ton

~ 550 million tons of biogenic CO_2 fixation per year

Please cite as: U.S. Department of Energy. 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. M.H. Langholtz, B.J. Stokes, and L.M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p. doi: 10.2172/1271651.

General Description	Biomass Criteria	Feedstocks	BiCRS Technology
WET, HIGH ASH	Moisture content: >25 wt.% Ash content: >10 wt.%	Sewage sludge	Anaerobic digestion, hydrothermal processing
WET, LOW ASH	Moisture content: >25 wt.% Ash content: <10 wt.%	Energy sorghum, green waste/yard, citrus residue, food waste, manure	Anaerobic digestion, hydrothermal processing, fermentation
DRY, HIGH ASH	Moisture content: <25 wt.% Ash content: >10 wt.%	Rice straw, tree nut residue, citrus residue, rice hulls, sugarcane trash, MSW wood	Combustion
DRY, LOW ASH, LOW LIGNIN	Moisture content: <25 wt.% Ash content: <10 wt.% Lignin content: <15 wt.% Holocellulose > 50%	Corn stover, switchgrass, sorghum, sugarcane bagasse, non-citrus residue	Hydrolysis + fermentation, gasification, pyrolysis
DRY, LOW ASH, HIGH LIGNIN	Moisture content: <25 wt.% Ash content: <10 wt.% Lignin content: >15 wt.%	Hardwood residue, softwood residue, mixed wood residue, other forest residue, Primary mill residue, secondary mill residue, cotton residue, cotton gin trash, tree nut residue construction and demolition waste, paper and paperboard,	Gasification, pyrolysis
HIGH OIL	Oil content: >30 wt. %	Algae, fat, oils, and grease (FOG)	Transesterification, hydroprocessing

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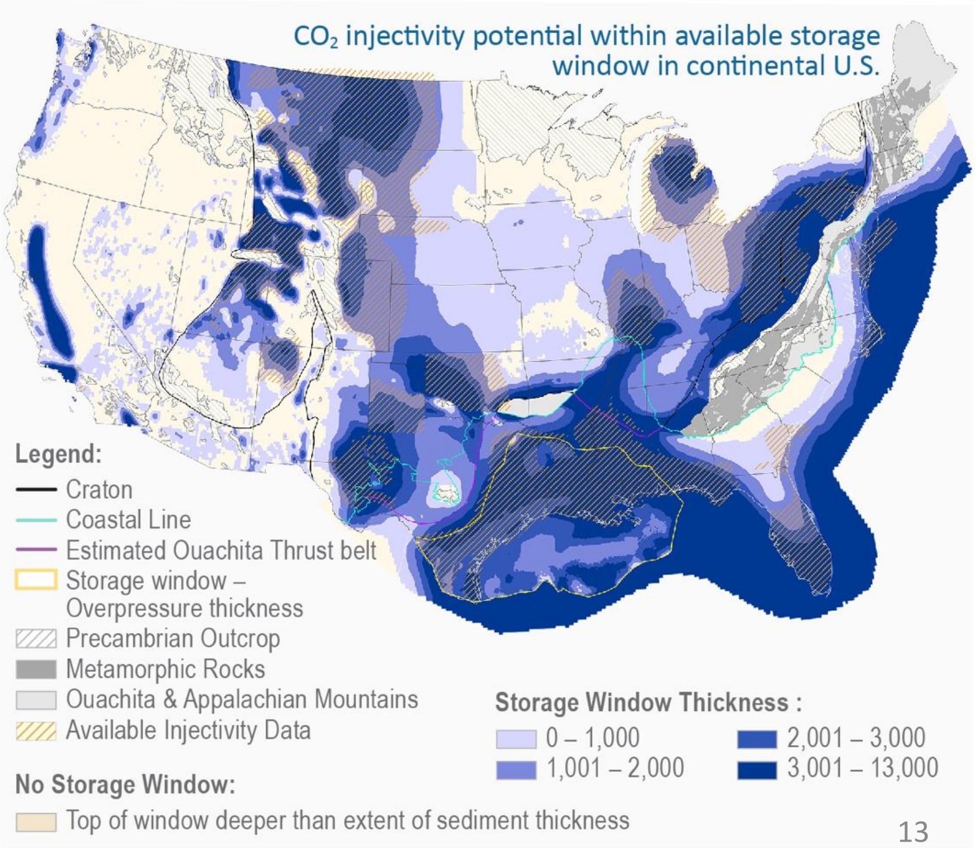
Biocarbon Sinks (Stabilization)

1. Geological sequestration of CO_2
2. Geological sequestration of bio-oil
3. Soil sequestration of biochar
4. Long lived products



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Near-Term BiCRS Bioproducts

- Bioenergy
- Bioplastics
- Biochar
- Fiber products

Bioenergy

Bioproducts:
- Hydrogen
- Alcohols
- Heat & power
- Methane
- Liquid hydrocarbons

Biocarbon sinks:
- Geological sequestration of CO_2
- Biochar sequestration in soil

BiCRS potential:
- ~5.0 $GtCO_2$ per year (upper limit)

Photosynthesis:	$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$
Combustion:	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{heat}$
Gasification:	$C_6H_{12}O_6 + 3O_2 \rightarrow 6CO_2 + 6H_2$
Pyrolysis:	$C_6H_{12}O_6 \rightarrow 4CO + 4H_2 + 2H_2O + 2C$
Fermentation:	$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$
Anaerobic digestion:	$C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2$
Hydroprocessing:	$C_6H_{12}O_6 + 7H_2 \rightarrow C_6H_{14} + 6H_2O$

Bioplastics

Bioproducts:

- Biodegradable bioplastics
- Non-biodegradable bioplastics

Biocarbon sinks:

- Long lived products (non-biodegradable)

BiCRS potential:

- ~2.0 GtCO_2 per year (upper limit)

Petroplastics → Bioplastics → BiCRS?

Current production of plastics: 380 million tonnes per year

~ 285 million tonnes of carbon

~ 1 billion tonnes of CO_2

2050 production of plastics: 1 billion tonnes per year

~ 750 million tonnes of carbon

~ 2.75 billion tonnes of CO_2

Meys et al. 2021, Smeaton et al. 2021

Bioplastics

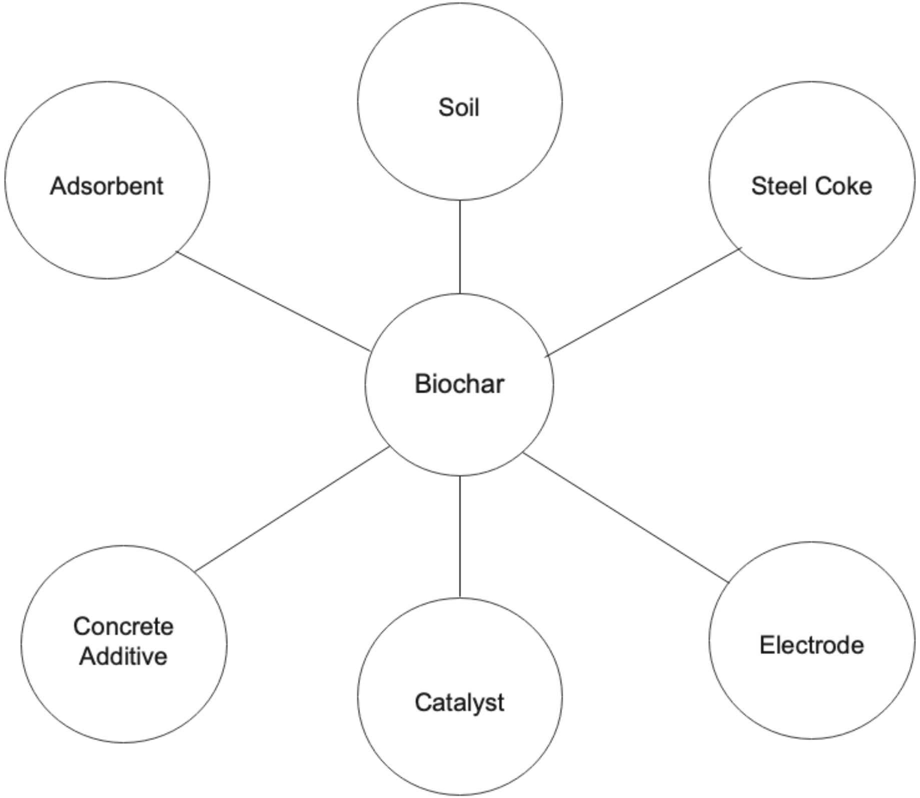
Bioplastics represent < 1% of total plastics

~36% of bioplastics are non-biodegradable

Bio-based/Non-biodegradable	% of Total	Biodegradable	% of Total
PE	9.5	PBAT	19.2
PA	9.1	PLA	18.9
PTT	8.1	Starch Blends	16.4
PET	6.2	PBS	3.5
PP	1.9	Cellulose Films	3.2
Other	1.0	PHA	1.8
PEF	0.0	Other	1.2

Department of Ecology, State of Washington 2014, European Bioplastics 2021

Biochar



Biocarbon sinks:
- Soil sequestration of biochar
- Geological sequestration of bio-oil
- Long lived products

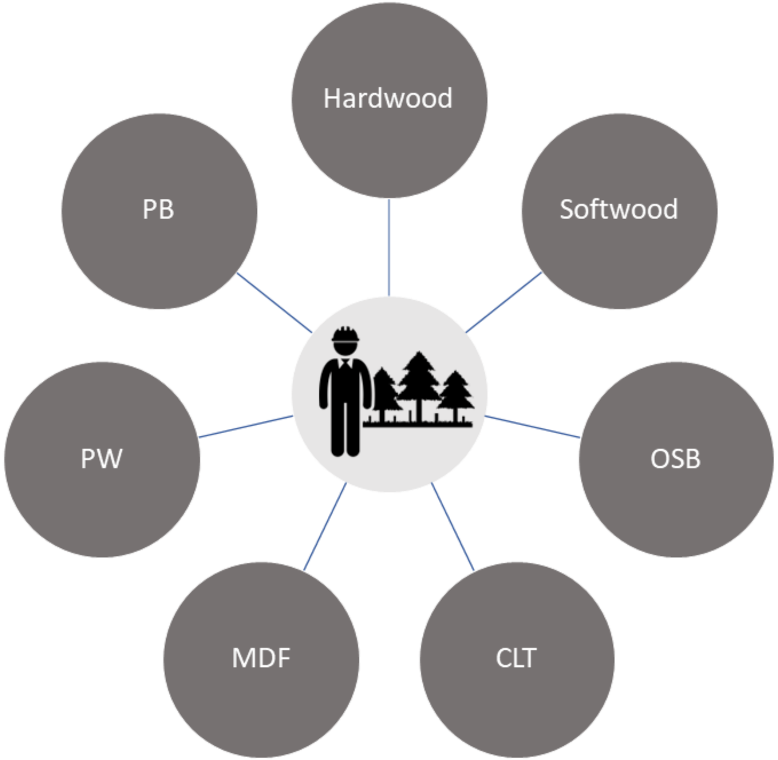
BiCRS potential:
- > 2 $GtCO_2$ per year

Biochar

Pros	Cons
Reduction in runoff	Potential leaching of heavy metals and polycyclic aromatics
Decrease in soil organic carbon priming	Efficacy dependent on many variables
Potential for high carbon permanence	Relatively expensive
Reduction in N_2O emisions	Lack of robust LCA data
Increase in crop yields when applied at appropriate dosages	Decrease in crop yields when applied at excessive dosages

Woodley et al 2021, Zhang et al 2019, Wang et al 2016, Brassard et al 2016, Leng et al 2018, El-Nagger et al 2019

Fiber Products



Biocarbon sinks:

- Long lived products

BiCRS potential:

- > 0.5 GtCO_2 per year

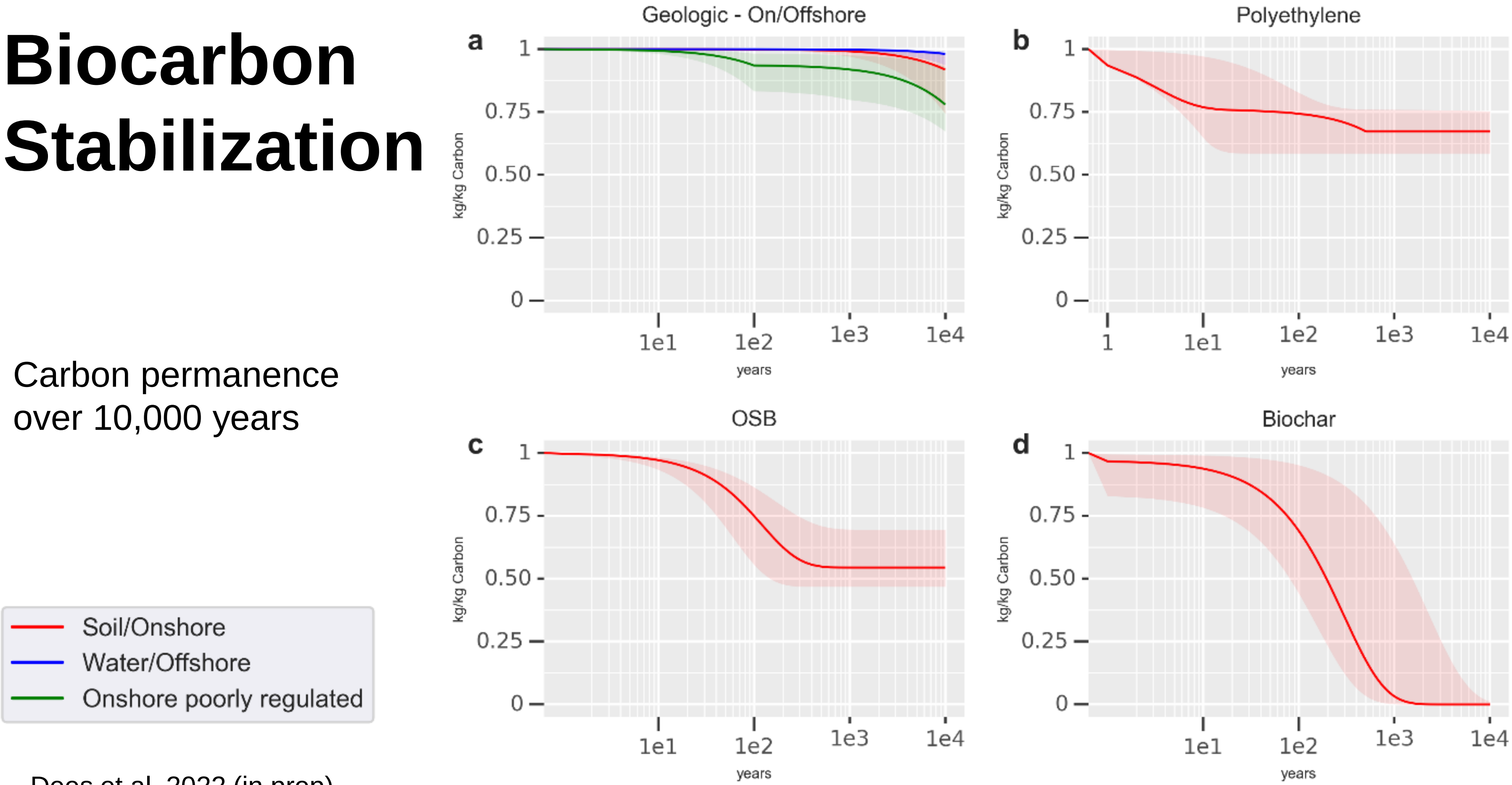
Fiber Products

- In the US, > 100 million tonnes of CO_2 are removed and incorporated into wood products each year
- Most lumber products store > 50% of their carbon for at least 100 years
- In the US, the pulp and paper industry emits ~115 million tonnes of biogenic CO_2 each year

Skog et al 2008, Saud et al 2015

Biocarbon Stabilization

Carbon permanence over 10,000 years



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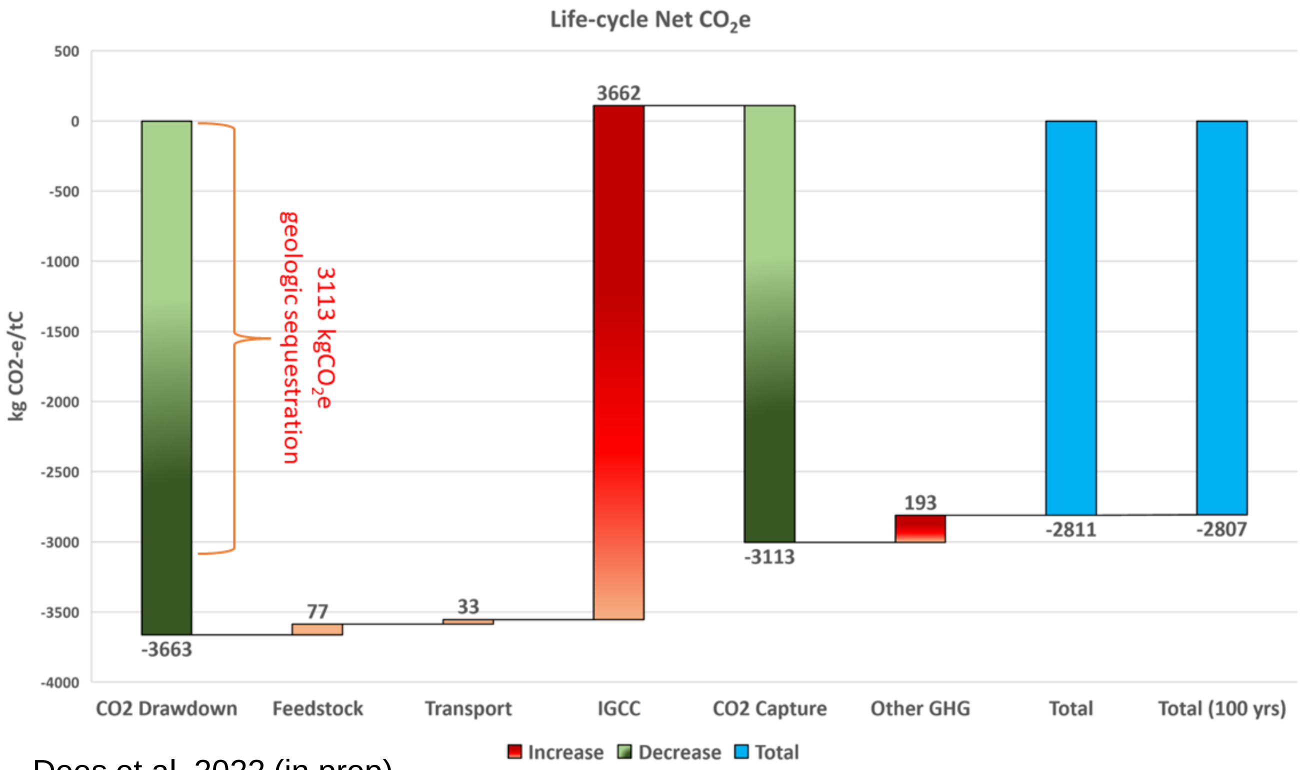
Case Study:
Bioelectricity from Switchgrass with CCS



77% of biologically fixed carbon contributes to removal for at least 1,000 years

70% for at least 10,000 years

While also providing value via hydrogen gas

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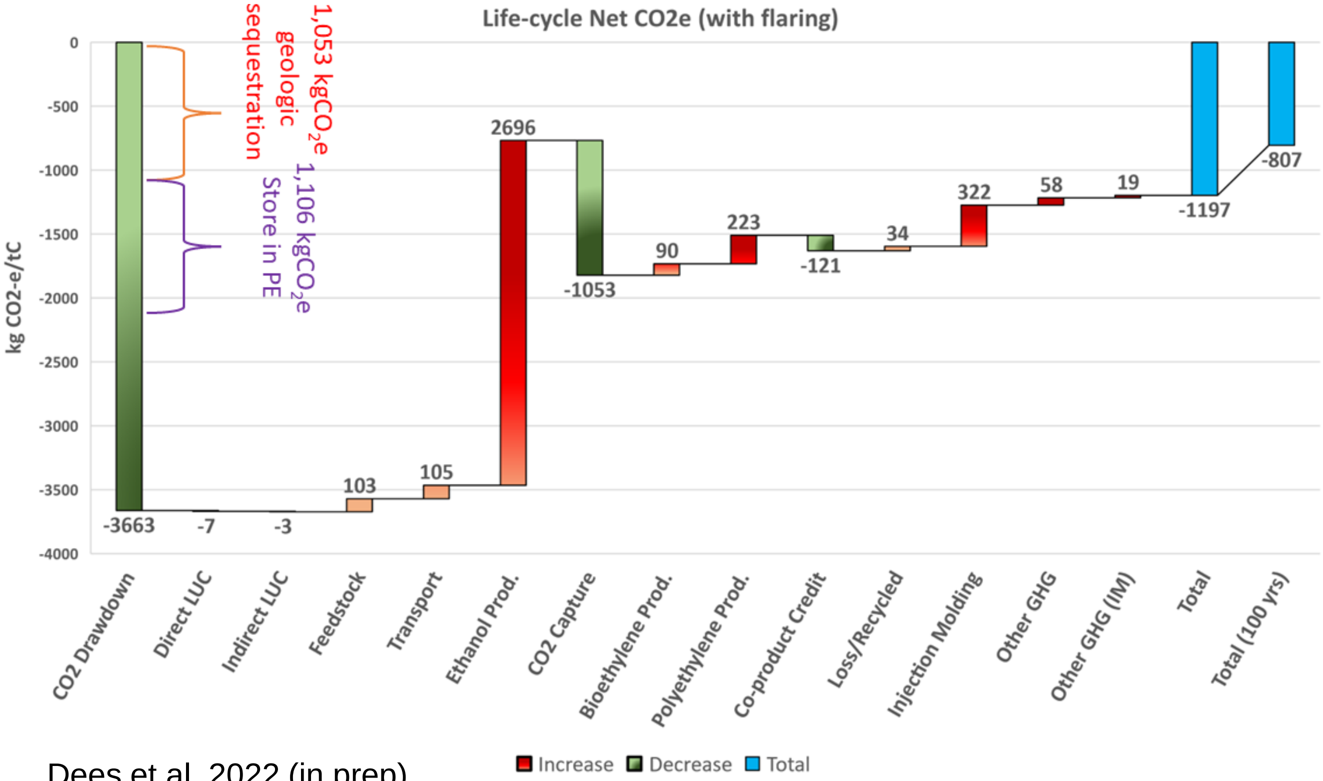
Case Study:
Polyethylene from Corn Stover with CCS



22% of biologically fixed carbon contributes to removal for at least 100 years

While also providing value via polyethylene plastic

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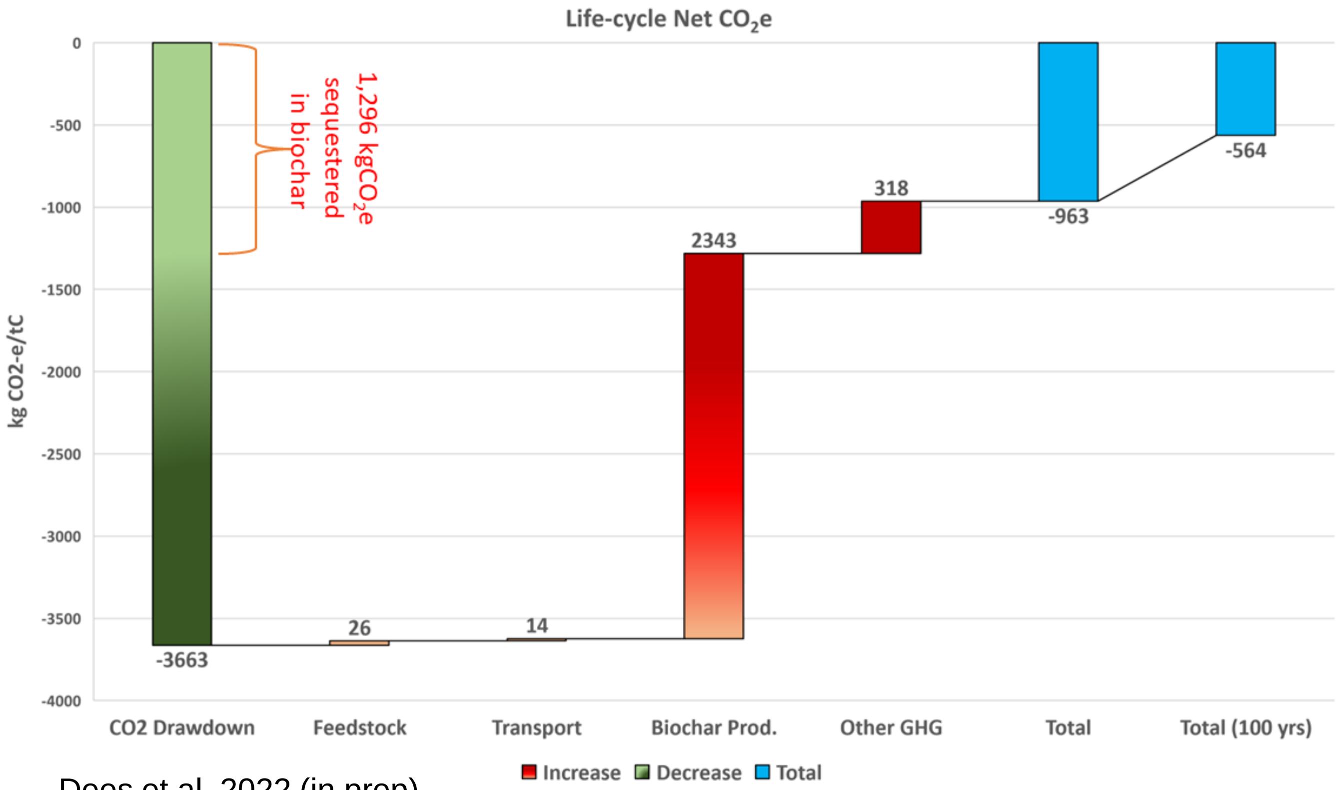
Case Study:
Biochar from Forest Residue



15% of biologically fixed carbon contributes to removal for at least 100 years

While also providing value via soil health enhancement

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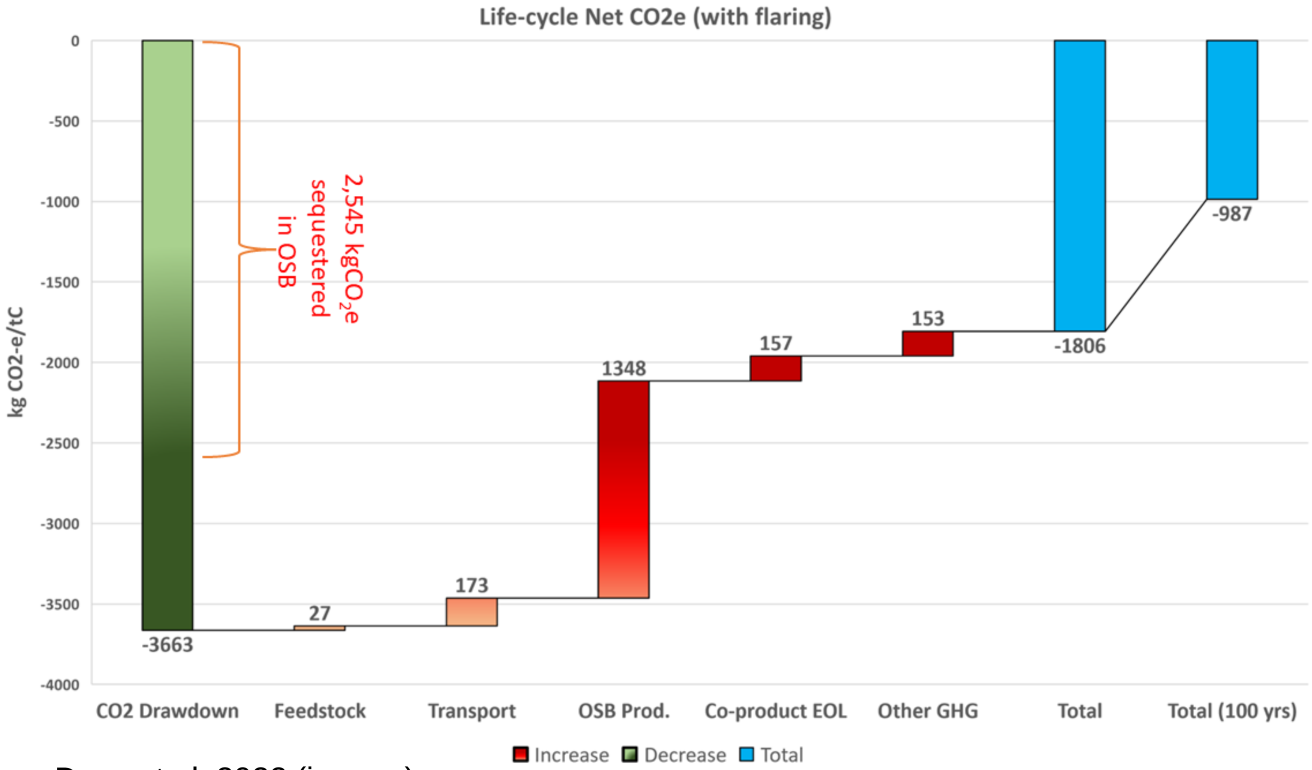
Case Study:
Oriented Strand Board (OSB) from Forest Residues



27% of biologically fixed carbon contributes to removal for at least 100 years

While also providing value via construction materials

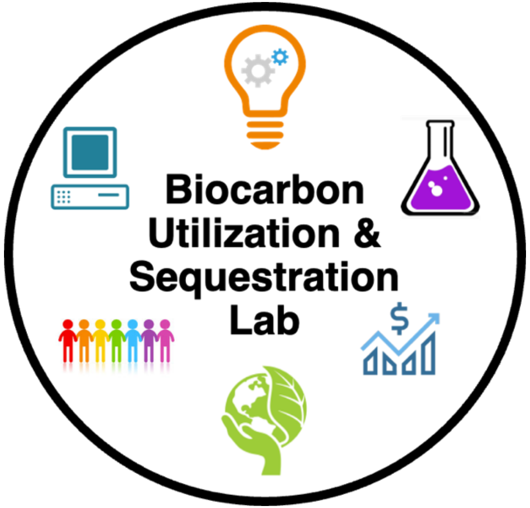
Dees et al. 2022 (in prep)

Low TRL BiCRS Products & Sinks

- Microbial assimilation of biogenic CO_2 into bioproducts
- Methane pyrolysis for hydrogen and graphite/carbon black
- Biocoke reductant in steel refining
- Biochar additive in concrete
- Mineralization of biogenic CO_2 into carbonate materials
- Deep ocean sequestration of macroalgae
- Bioenergy-driven direct air capture

Conclusions

- **Near-term** opportunities to leverage the bioeconomy for carbon drawdown via BiCRS
- **Biocarbon sources:** vary depending on region and conversion pathway
- **Biocarbon conversion**: pyrolysis, gasification, combustion, anaerobic digestion, and fermentation
- **Bioproducts**: bioenergy, biochar, bioplastics, and fiber materials
- **Biocarbon sinks (stabilization)**: geological sequestration of CO_2, geological sequestration of bio-oil, biochar soil sequestration, and long lived products



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